Determination of «survivability» index of technological equipment under the threat of failure

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Abstract. Timely monitoring of the condition of the equipment is an urgent task. The paper presents the results of research on methods of monitoring of technological equipment, namely, the developed method of determining the index of "survivability", which allows evaluating and predicting the condition of the unit between maintenance operations. The paper also presents the results of the study of monitoring and control systems of technological equipment, namely, the assessment of the "survivability" indicator and its prediction in the STATISTICA program by the exponential smoothing method.

Keywords: Condition monitoring, Diagnostics, Vitality index, Reliability assessment, Comprehensive analysis.

1 Introduction

Large-scale distributed technological objects consist of elements of technological equipment combined into technological complexes.

The absence of a system that includes end-to-end monitoring increases the economic risks of the enterprise, as well as the risks of security breaches, including environmental and energy. Its presence, in turn, allows you to additionally automate the ongoing processes, to carry out timely control over changes in performance indicators.

Within the framework of this article, the improvement of the system for monitoring the technical state of distributed technological objects of oil refineries will be considered on the basis of a comprehensive analysis of vibration indicators and the development of a block diagram of the unit for analyzing equipment parameters.

2 Assessment of the state of technological equipment

Currently, to assess the reliability of complex technical processes and the types of equipment used in them, a large number of working documents, standards [1-2], technical conditions and other regulatory frameworks have been circulated. Let us study the procedure for carrying out work to assess reliability indicators in accordance with RD 50-690-89 [3]:

a) selection of a reliability test plan;

b) test planning;

c) collection of the necessary information;

d) statistical processing of information.

The final stage is statistical processing of information to assess the reliability indicator, carried out by two methods:

- a nonparametric method with an unknown distribution law, including a direct assessment of reliability indicators;
- a parametric method in which the distribution law is known, which also includes an estimate of the distribution law parameters included in the formula for calculating the estimated reliability indicator, and an estimate of the reliability indicator based on the calculated estimates of the distribution law parameters.

Parametric methods for assessing reliability indicators established in RD 50-690-89 are used for exponential, normal, lognormal and diffusion distributions and Weibull distribution in the situations indicated in Table 1.

In the nonparametric method, the problem of determining the distribution function and its parameters is not posed. It is necessary to evaluate the values of the reliability indicators of the evaluated equipment according to the operational data.

The disadvantage of the presented technique is its statistical nature. The indicators to be assessed are averaged over a large time period, therefore, the forecast with such data without taking into account causal relationships and functional analysis of the reliability models of objects is approximate

Table 1. Typical situations for a parametric method for evaluating reliability indicators

Designation of typical situations	Brief description of typical situations
TS-1	Products of the same type are in the same conditions and the reliability indicators of these elements are the same
TS-2	Products of the same type are in different conditions. The ratios of the parameters of the distribution laws of elements are known
TS-3	Products of the same type are in different conditions. The ranges of variation of the ratio of the parameters are known depending on the location in certain conditions
TS-4	Products of the same type are in different conditions. It is a known fact that the indicators in some conditions are higher than in others

The problem of the lack of representative samples of failures in some cases makes it impractical to implement the recommendations of RD 50-690-89 and similar documents.

3 The indicator of "survivability" of technological equipment

The indicator of "survivability" is a dimensionless value that reflects the ability of the equipment to work before maintenance while maintaining the trends of the main technical characteristics without the occurrence of a certain malfunction [4].

The indicator of "survivability" is determined individually for each type of failure, since it directly depends on the number of diagnostic parameters, according to which the presence of a malfunction is recorded, or rather, on the deviations of real values from the target trends. Mathematically, it can be described as follows:

$$P_S = \sum w_{i,j} \; ,$$

where w is the deviation of the real value of the parameter from the target;

i - diagnostic parameter;

j - is the type of failure.

The following expression is proposed for determining the indicator of "survivability" of equipment at time t:

$$P_S\left(\sum_{i=1}^{n} w_i, t\right) = k \cdot \left(1 - \sum_{i=1}^{n} \frac{w_i}{n}\right) + m \cdot e^{-\lambda(T-t)} \tag{1}$$

4 Determination of the "survivability" index of technological equipment

Table 2 presents the diagnostic parameters and their corresponding types of trends

Table 2. Parameters of the third additional study

The diagnostic parameter	Kind of trend
Pressure	normal
Bearing temperature	escalating
Vibration velocity of the node	normal

Figure 1 shows a diagram of the change in the "survivability" indicator for the study

Knowing that at time T there is scheduled maintenance, determine the relative change in the index "survivability" at time T from its value at time t_0:

$$\Delta_B = \frac{P_S(T)}{P_S(t_0)}. \tag{2}$$

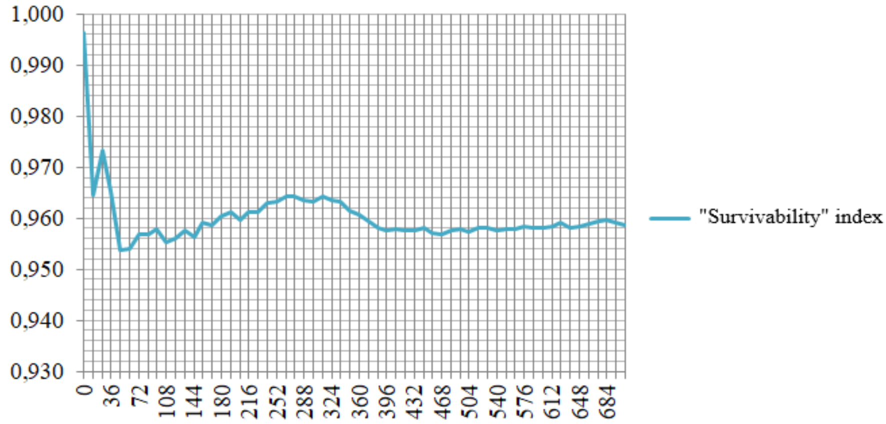

Fig. 1. Diagram of changes in the "survivability" indicator for the study

We make calculations for all the studies and enter the results in Table 3.

Table 3. Determination of the relative change in the "survivability" parameter

Study number	Δ, %	Δ_{mid}, %
1	95,35	95,08
2	93,32	
3	95,48	
4	96,20	

Based on the results of the calculations, we can conclude about the value of the upper limit of the indicator "survivability": when the P_S decreases below 95% of the maximum value it is necessary to carry out minimum maintenance of equipment (inspection, check leaks, the appearance of noise and other characteristic markers of failure).

To determine the lower boundary of the P_S, at reaching which an urgent unscheduled repair is necessary, it is necessary to use the prediction of the resulting time series.

5 Predicting the "survivability" index

We select several key parameters, with the help of which we will further predict the probability of failure until the nearest maintenance:

- vibration characteristics (in our case, vibration velocity);
- the head produced by the pump;
- bearing temperature.

We will use the data samples obtained from the database of artificially simulated time series to construct graphs of indicators change in time [5].

The production head of the pump varies in the interval [50-5%; 50+7%]; the maximum bearing temperature must not exceed the room temperature by more than 50°C and the set limit value of 363 K (90°C); the limit value of the vibration velocity of some units of the equipment does not exceed 11.2 mm/sec and cannot exceed the value of the indicator equal to 7.1 mm/sec for more than 30 days.

Samples consist of 60 indicators of a certain parameter, recorded every 12 hours. The choice of the time range is due to the manufacturer's recommended maintenance period [6], and is about 700-730 hours.

As a result of construction of diagrams of changes of parameters in time, as well as limit and target trend lines [7], the following graphs were obtained (Fig. 2, 3, 4).

After calculating the total maximum deviations, we determine the value of the deviation at each moment of time, summarize these deviations, and then normalize each of the indicators by the following formula:

$$w_i = \frac{\Delta q_i}{(\sum \Delta Q)_i}, \tag{3}$$

where w_i – is the normalized deviation;

Δq_i - the value of the deviation at time t;

$(\sum \Delta Q)_i$ - is the value of the total maximum deviation from the trend at time t.

We calculate the first and second terms of equation 3, given the values of the tuning coefficients k, m, and λ. After that, we determine the survivability index of the equipment for the initially proposed type of failure.

The change in the survivability index over time is shown in Figure 5.

In the period from 0 to 84 hours, the survivability index decreased, which may indicate the equipment running-in phase. Any deviations of diagnostic parameters during this time show that the equipment enters normal operation mode, and its parameters are only approaching the trend lines.

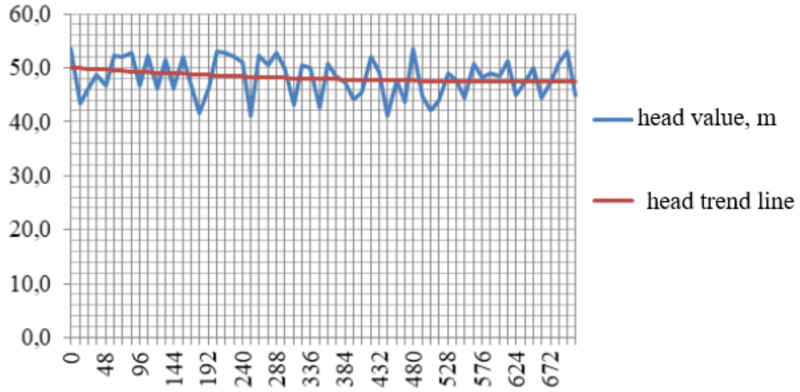

Fig. 2. Diagram of head changes of pump K 80-50-200-E

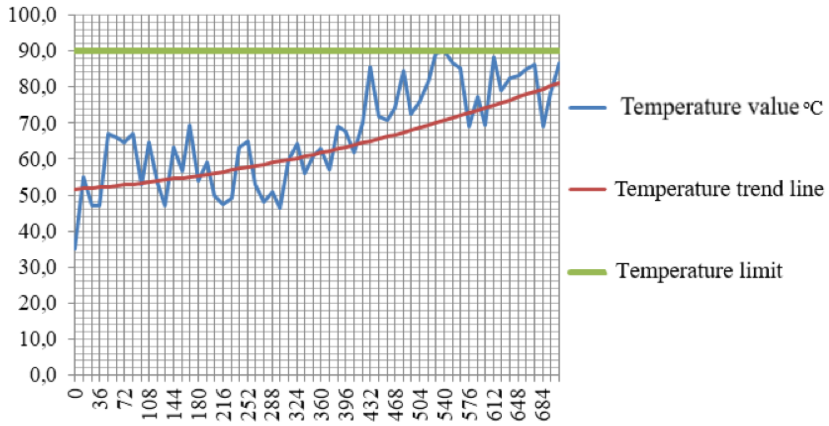

Fig. 3. Temperature variation diagram of the K 80-50-200-E pump bearing

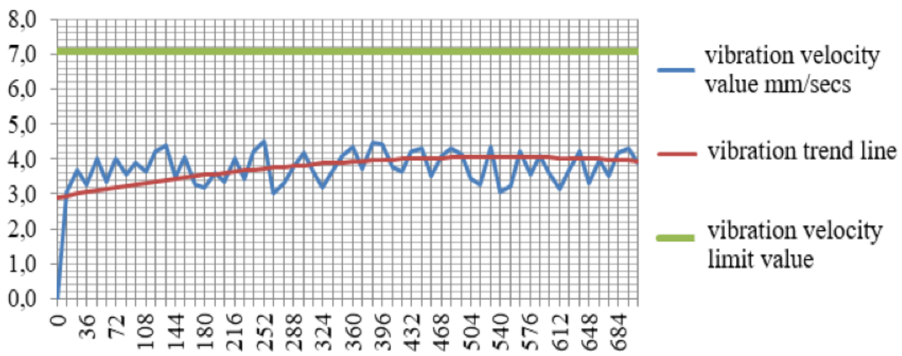

Fig. 4. Vibration velocity diagram of the investigated pump unit K 80-50-200-E

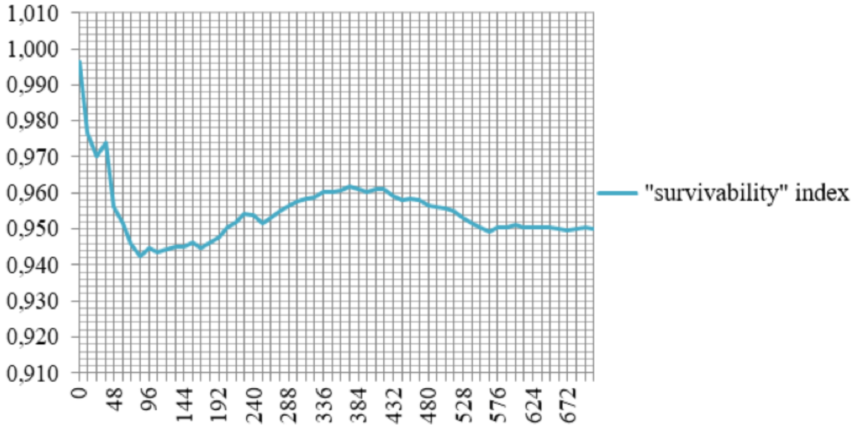

Fig. 5. Diagram of change in the "survivability" index of a centrifugal pump for one type of failures

Then the value starts to rise again and takes on values slightly deviating from the average value of approximately 0.950. This level is maintained for the remainder of the life of the pump before maintenance.

On the basis of one-time conducted research it is impossible to judge precisely about boundary values of "survivability" parameter, at which minimum maintenance up to planned maintenance is required, or equipment is taken out of operation for urgent repair, restoration of damaged unit and bringing of diagnostic parameters to the trend values. Therefore, it is proposed to conduct at least three additional studies, using the same diagnostic parameters, but changing the data samples. At the same time, the target trends of indicators of head, bearing temperature and vibration velocity of the unit remain the same, since we will assume that each of the studies was carried out on the same type of equipment

Next, we will use the software package STATISTICA to predict the index of "survivability".

Short-term or medium-term forecasting will be preferable in the conditions of the analysis unit. The most suitable forecasting methods are exponential smoothing and autoregressive integrated moving average (ARIMA).

Let us perform the forecasting of RL with the help of exponential smoothing.

To build the prediction, we choose the change in the "survivability" index obtained from the results of the first additional study, because the diagram (Fig. 6) shows the decrease in RR over time.

In STATISTICA program, we turn to the Time Series/Forecasting module. The next step is to assign the variable under study (Variables) - the index of "survivorship" from the original study.

Next, you should select the Exponential smoothing & forecasting item. This item offers 12 different variants of exponential smoothing models. For our case, the exponential model will be suitable.

To perform exponential smoothing for the selected model it is required to define two smoothing parameters - Alpha (α) and Gamma (γ).

For the smoothing parameter α, which is responsible for smoothing of the observations directly, the following is true: if α is 1, then the previous observations are completely ignored; if α is 0, then the current observations are ignored [8-9].

For the smoothing parameter γ, which is responsible for smoothing of the trend: If γ equals 0, the trend is constant for all values of the time series (and for all forecasts); if γ equals 1, the trend is determined mostly by observational errors.

We will search for the parameters using the Grid search tab. Here we set start, step and limit values for the parameters α and γ. Define these values, also select the item Display parameters for 10 smallest mean squares and click Perform grid search.

The window that opens displays a table with the 10 best models. The determining factor for model selection is the Mean Absolute Error shown in the outermost column.

Parameter grid search (Smallest abs. errors are highlighted) (Прогнозирование.sta)
Model: Expon. trend, no season ; S0=1,012 T0=,9702
Исследование №1

Model Number	Alpha	Gamma	Mean Error	Mean Abs Error	Sums of Squares	Mean Squares	Mean % Error	Mean Abs % Error
1850	0,721000	0,981000	0,000677	0,001771	0,000682	0,000011	0,070104	0,186003
1900	0,741000	0,981000	0,000659	0,001767	0,000683	0,000011	0,068220	0,185543
1800	0,701000	0,981000	0,000696	0,001778	0,000684	0,000011	0,072091	0,186834
1899	0,741000	0,961000	0,000673	0,001771	0,000686	0,000011	0,069642	0,185968
1849	0,721000	0,961000	0,000691	0,001776	0,000686	0,000011	0,071565	0,186524
1950	0,761000	0,981000	0,000642	0,001765	0,000687	0,000011	0,066429	0,185362
1750	0,681000	0,981000	0,000716	0,001790	0,000689	0,000011	0,074189	0,188112
1949	0,761000	0,961000	0,000655	0,001768	0,000689	0,000011	0,067815	0,185688
1799	0,701000	0,961000	0,000711	0,001785	0,000689	0,000011	0,073593	0,187501
1898	0,741000	0,941000	0,000687	0,001775	0,000690	0,000011	0,071126	0,186440

Fig. 6. Search result on the grid

The model with the lowest mean absolute error (1950) has the following parameters α and γ:

α = 0,761;

γ = 0,981.

We select 14 periods for the forecast, which will be equal to 168 hours of equipment operation or one week. Then click OK (Summary) and we get the graph shown in Figure 7.

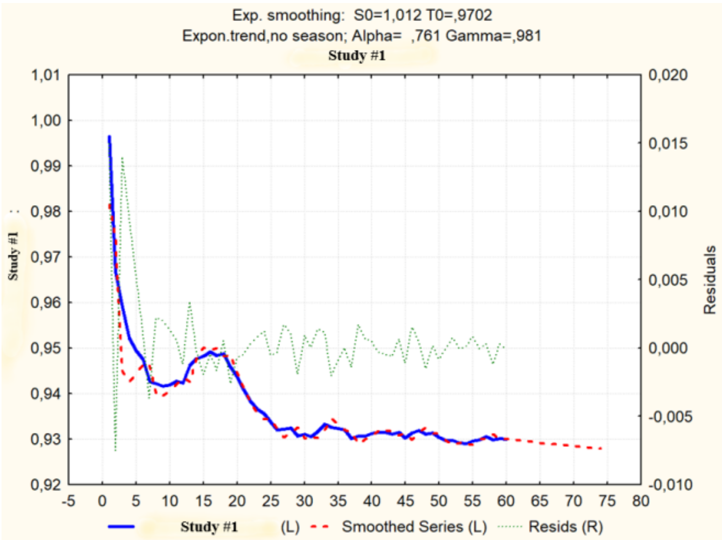

Fig. 7. Exponential smoothing

The blue color on the graph shows the real values of the "survivability" indicator, the red dotted line - the forecast that is obtained by using exponential smoothing.

The green dotted line is the residuals corresponding to the difference between the actual values and the values obtained by smoothing. The residuals for a longer period of operation of the equipment do not exceed ±0.0025.

It follows from the graph that if the equipment continues to operate after the time of planned maintenance without its implementation, the indicator "survivability" will continue to decline and after 168 hours will reach the value of 0.927 (Table 4).

Table 4. Prediction results with exponential smoothing

Period	Time of operation, hours	The value of the "survivability" indicator
61	720	0,929828
62	732	0,929680
63	744	0,929532
64	756	0,929384
65	768	0,929236
66	780	0,929089
67	792	0,928941
68	804	0,928793
69	816	0,928645
70	828	0,928498
71	840	0,928350
72	852	0,928202
73	864	0,928055
74	876	0,927907

In order to compare the results, we make a prediction using the ARIMA method.

In the STATISTICA program we access the module Time Series/Forecasting. The next step is to select the variable under study (Variables) - the index of "survivability" from the initial study and construct a linear graph for it. Press the OK button and in the dialog box that opens select the Plot of the selected variable in the Review & plot tab.

For further verification of the time series it is necessary to perform the autocorrelation analysis.

In the previous dialog box, select the Autocorrelations tab (Autocorrs). We set the number of lags to 14, which in our case will correspond to 14 periods of measurements or 168 hours of equipment operation (one week). Then we build an autocorrelation function (Autocorrelations).

The resulting autocorrelation function is shown in Figure 8.

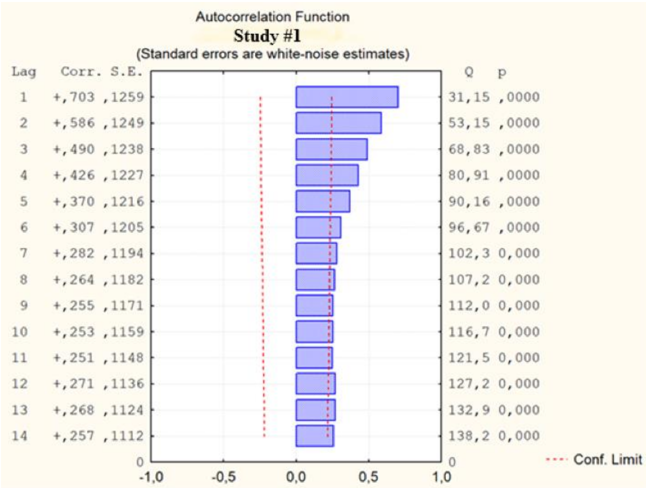

Fig. 8. Autocorrelation function

According to the results of the autocorrelation function, the first lag (measurement period) is highly significant and significantly exceeds the limits of the confidence interval.

Let us remove the significant value of autocorrelation by taking the difference of the order of 1. Return to the analysis dialog box and in the Difference, Integrate tab assign the value of lags equal to 1 in the Difference item. After that press OK and we obtain the transformed time series. To check if the autocorrelation value was changed at the first lag, it is necessary to plot the autocorrelation function for the transformed time series (Figure 9).

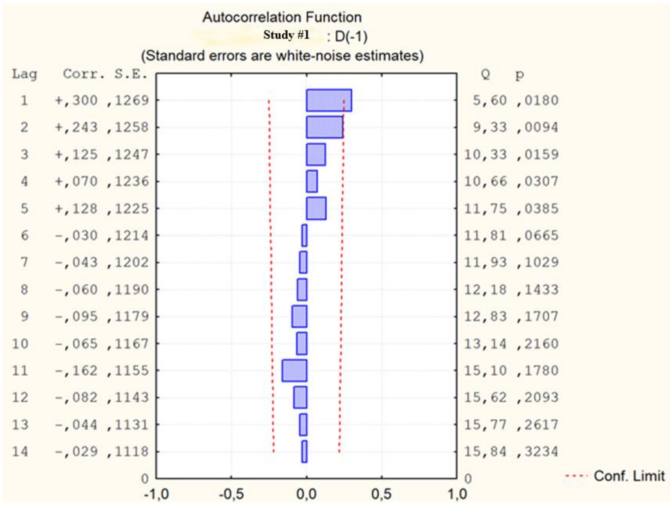

Fig. 9. Autocorrelation function of the transformed time series

Taking the difference with lag 1 led to a decrease in the autocorrelation function on the corresponding lag. Also, based on the obtained graph, we confirm the absence of any periodicity (seasonality).

To select the parameters of the ARPSS model, it is necessary to construct two functions, the autocorrelation function and the partial autocorrelation function for the transformed series.

To build the partial autocorrelation function, select the item Partial Autocorrelations in the tab Autocorrelations.

Figure 10 shows the resulting partial autocorrelation function.

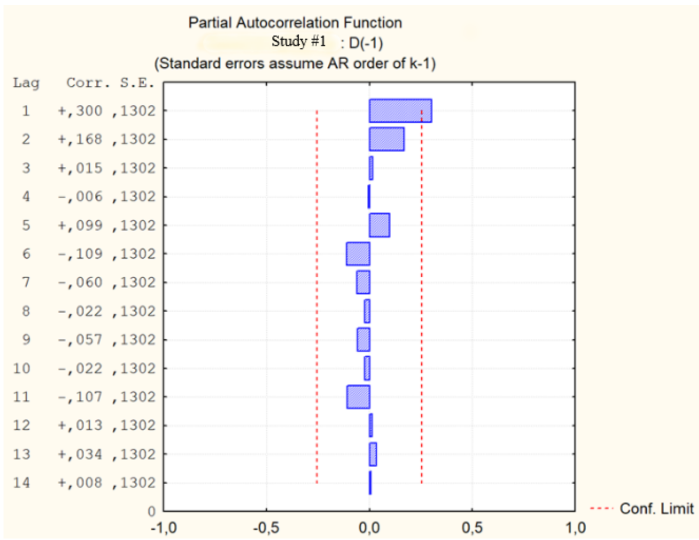

Fig. 10. Partial autocorrelation function of the transformed time series

For the partial autocorrelation we observe the following: no significant lags, no seasonality, the graph decays exponentially.

According to the rules for determining the ARPSS parameters, we draw the following conclusions:

- if the autocorrelation function decreases exponentially and the partial autocorrelation function has a sharply prominent value for lag 1, and there are no correlations at other lags, then the p value corresponding to autoregression (Autoregression, AR) is 1;
- If the autocorrelation function has a sharply distinctive value at lag 1, there are no correlations at other lags, and the partial autocorrelation function exponentially decreases, then the index q corresponding to the Moving Average (MA) equals 1.

Let's return to the time series analysis menu. In order to estimate the prediction error, we select a part of the data from the sample for cross-checking. To do this, it will be necessary to exclude a certain range of data from the time series. In the Condition item we set the range of observations from 1 to 46. Then 47-60 observations will remain for cross-checking.

In the time series analysis menu, select ARIMA & autocorrelation functions. In the dialog box that opens, set the parameters that were previously defined.

In the ARIMA-model menu, select the Advanced tab. In order to obtain numerical values of the predicted data, as well as the graph of the forecast, let's set:

- number of observations (number of cases) - 14;
- start at case - 47;
- confidence interval - 0,65.

We decrease the confidence interval from 90% to 65% in order to narrow the forecasting range, which will make it possible to obtain more accurate forecast values.

Then select the items Forecast and Plot series & forecasts. The numerical results of the forecast and their graphical representation are shown below (Figure 11).

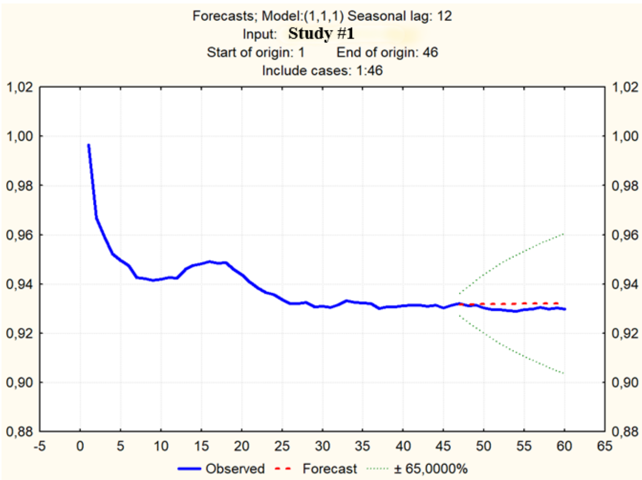

Fig. 11. The graph of the "survivability" indicator with the ARIMA model verification

Let's perform cross-check to determine the value of absolute error of predicted values of time series. The results of cross-check are presented in Table 5.

Table 5. The result of cross-checking the predicted series

No.	Observable series	Predicted series	The magnitude of the absolute error
47	0,9311	0,931599	0,00047
48	0,9313	0,931727	0,00035
49	0,9303	0,931816	0,0015
50	0,9297	0,931879	0,0023
51	0,9296	0,931922	0,0024
52	0,9291	0,931953	0,0030
53	0,9289	0,931975	0,0032
54	0,9296	0,931990	0,0025
55	0,9298	0,932001	0,0023
56	0,9305	0,932008	0,0016
57	0,9298	0,932013	0,0023
58	0,9302	0,932017	0,0019
59	0,9299	0,932020	0,0022
60	0,9311	0,931599	0,00047

The magnitude of the error is extremely small, which allows us to conclude that this prediction method is also suitable for use in the parameter analysis block.

6 Conclusion

The study examined one of the key tasks of rational operation of refinery units - monitoring the condition of equipment. Untimely monitoring of increasing operational and functional indicators of units leads to sudden breakdowns and accidents.
We developed an analysis unit based on determining the parameter "survivorship" - a dimensionless value, reflecting the ability of the equipment to keep working until the moment of maintenance, as well as predict the possibility of operating the unit without maintenance, while maintaining the same level of trends in the main diagnostic parameters.

Use of complex analysis of parameters, characterizing state of equipment, will allow personnel to receive timely signals about occurrence of failures and to eliminate them, avoiding damage of technological equipment, disturbance of technological process and providing safety of personnel. These measures, in case of sudden breakage or accident, make it possible to prevent economic losses of the enterprise.

Due to timely control, it becomes possible to predict the condition of the equipment before and after the scheduled maintenance. For this purpose, the method of forecasting the index of "survivability" of technological equipment in the STATISTICA program was considered and developed.

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